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Modelling the impact of land use management on water resources in a tropical inland valley catchment of central Uganda, East Africa

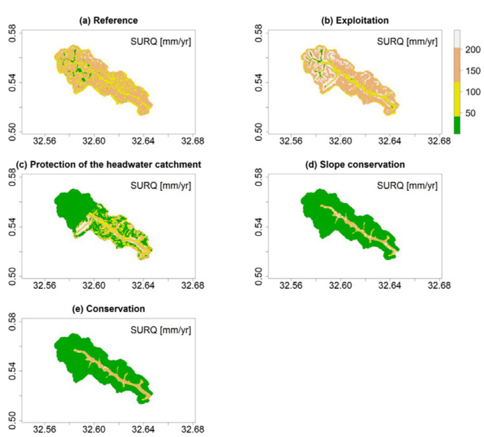
Geoffrey Gabiri [a,*], Constanze Leemhuis [b], Bernd Diekkrüger [a], Kristian Näschen [a], Stefanie Steinbach [a], Frank Thonfeld [a]

[a] *Department of Geography, University of Bonn, 53115 Bonn, Germany*
[b] *Department of Environment and Sustainability, DLR Project Management Agency, Heinrich-Konen-Straße 1, 53227 Bonn, Germany*

HIGHLIGHTS

- Poor management and increasing exploitation hamper sustainable use of inland valleys.
- ArcSWAT2012 and SWATgrid were applied to an inland valley in Namulonge, Uganda.
- Four land use scenarios were analyzed for their hydrological impact.
- Results show a strong relationship between land use management and water yield.
- SWATgrid can consider and simulate spatial patterns of properties and fluxes.

GRAPHICAL ABSTRACT



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ABSTRACT

A combination of climate change, food demand, population growth, and other driving forces are causing land use and land cover change (LULC) in wetlands of Sub Saharan Africa (SSA). This has a profound effect on water resources, thus it is imperative that such consequences arising from these changes are predicted accurately to support land use management. For that, local scale studies are required to understand the system and to perform scenario analysis. The focus of this study was on small scale inland valleys which are common in SSA. The impact of LULC on the hydrological processes in a tropical inland valley was investigated. A hydrological response unit (HRU)-based (ArcSWAT2012) and a grid-based setup (SWATgrid) of the Soil Water Assessment Tool (SWAT) model are applied. Good model performance was achieved after calibration and validation with daily discharge (R^2 and NSE > 0.7 for both model setups). Annual water balance indicates that 849.5 mm representing 65% of precipitation is lost via evapotranspiration. Surface runoff (77.9 mm) and lateral flow (86.5 mm) are the highest contributors to stream flow in the inland valley. Four land use management options are developed in addition to the current land use system, with different water resources conservation levels (*Conservation*, *Slope conservation*, *Protection of headwater catchment*, and *Exploitation*). There is a strong relationship between the first three management options with decreasing surface runoff, annual discharge and water yield while the fourth option will increase annual discharge and total water yield. This suggests that if poor management and increasing

* Corresponding author.
E-mail address: geoffreygabiri@gmail.com (G. Gabiri).

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exploitation of the inland valleys persist, the availability of water resources for human consumption and plant growth will decrease. This study contributes to improving the scientific knowledge on the impact of land use change on hydrological processes in the catchment-wetland nexus to support sustainable water resources management.

1. Introduction

Wetlands consisting mainly of alluvial floodplains and inland valleys are estimated to cover about 4.7% in Sub Saharan Africa (SSA) (Rebelo et al., 2010). In East Africa, wetlands cover an area of about 0.15 million square kilometers (Amler et al., 2015), from which 80% is covered by inland valley wetlands (Sakané et al., 2011; Leemhuis et al., 2016). Inland valleys are defined as flat, relatively shallow valleys, which are widespread in undulating landscapes. They are characterized by a valley bottom, hydromorphic fringe, seasonally water logged depression and an upstream position relative to a hydrological network (Rodenburg et al., 2014). Inland valleys offer a range of ecosystem services (Rebelo et al., 2010; Russi et al., 2013) for livelihood and are vital in River Basin Management (Ramsar Convention on Wetlands, 2018).

In fact, in SSA, inland valleys are seen as potential niches for agricultural expansion (Rodenburg et al., 2014; Dossou-Yovo et al., 2017). This is due to the declining quantity and quality of upland arable land for productivity (Beuel et al., 2016). Further, their nutrient rich soils and the prolonged water availability throughout the year induce potential interest for agricultural intensification to achieve food security (Böhme et al., 2013; Dossou-Yovo et al., 2017). Besides being potential niches for agricultural production, inland valleys provide a range of regulating, cultural and supporting services to the communities (Rebelo et al., 2010).

Despite of these values to the communities, inland valleys are becoming threatened because of the ongoing land use and land cover (LULC) change in SSA. The LULC change is a result of increasing socio-economic development and population pressure with a concomitant increase for food demands (Thornton et al., 2010; Sakané et al., 2011). Climate change, urbanization and limited information on the consequences of land use changes (Turner et al., 2000; Schuyt, 2005) have also triggered LULC change. A decline of over 53.8% of wetlands (inland valleys inclusive) in the Lake Victoria basin and 14.7% in the Lake Albert basin have been reported (Uganda wetland atlas, 2016). The uncontrolled transformation of pristine wetlands to different land uses significantly changes their biophysical state, ultimately affecting the quantity and quality of water resources (Dixon and Wood, 2003; Motsumi et al., 2012). These changes have impacts on the hydrological functioning and response of the wetland and their surrounding catchments (Troy et al., 2007). The linkage between wetlands and their surrounding catchments from where water and sediments are derived, and the effect of land use changes influence the spatio-temporal distribution of the hydrological processes (Wood et al., 2013).

Considering the geomorphological setting of the inland valley wetland, surface and subsurface inflow may have a strong impact on its water balance besides precipitation (Leemhuis et al., 2016). Factors such as land use management and climate variability within the wetland and its surrounding catchment mainly influence seasonal water availability. Land use change associated with intensive agriculture and rapid urbanization may cause severe impacts on the wetland ecosystem services by influencing water quantity and quality (Chien et al., 2013). Therefore, water availability for crop production could be affected particularly in water resources limited areas (Liew et al., 2012).

Wetlands can't be described and managed as isolated ecosystems but the surrounding catchment needs to be considered in a nested wetland-catchment approach, to assess the spatial and temporal distribution of the hydrological processes within the catchment context (Von der Heyden and New, 2003). A better understanding of the wetland-catchment interaction and how LULC change influences their hydrology may guide water resource managers in sustainable land use planning and water resources management (Dixon and Wood, 2003; Ramsar Convention Secretariat, 2010; Dossou-Yovo et al., 2017; Liu et al., 2017).

The functional landscape approach (FLA) has been developed as a potential strategy to achieve sustainable wetland use and enhance ecosystem services for livelihood development in SSA (Wood et al., 2013). Accordingly, the FLA recognizes that wetland sustainability is based on biophysical processes not only in the wetlands but also in their surrounding catchments, i.e. maintaining a balance of ecosystem service use within the wetlands as well as improving land use management in the catchment. This approach has been successfully applied and qualitatively evaluated in Malawi, Southeast Africa (Wood et al., 2013). However, the quantitative impact of the different land use management options implemented on the hydrological processes is not clearly documented. Yet quantitative impact analysis of these land use management options on the hydrology is vital in guiding decision making on land use planning and water resources at wetland – catchment scale.

Quantitative impact analysis of land use management on water resources at different spatial and temporal scales, more so at the wetland - catchment level, requires hydrological modelling (Agarwal et al., 2002). The impact of LULC change on water resources is dependent on the studied scale (Wagner et al., 2013), LULC type (Leemhuis et al., 2007), and the local climate (Descroix et al., 2009). Hydrological models have been used as supporting tools to improve the understanding and sensitivity of hydrological processes to land use changes (Lambin et al., 2000). Several studies have demonstrated the suitability of hydrological models in assessing LULC change impact on water resources of tropical climate (e.g. Cornelissen et al., 2013; Aduah et al., 2018; Kasuni and Kitheka, 2017; Tsarouchi and Buytaert, 2018). However, different models may result in diverse outcomes due to their differences in perceptual, conceptual, and procedural concepts (Beven, 2012). Application of physically based semi-distributed hydrological models represent the fundamental hydrologic processes in details (Beven, 2012). LULC change impact on hydrologic pathways has been successfully assessed by the physically based hydrological models in the agricultural catchments (Tuppad et al., 2010; Wagner et al., 2013; Yira et al., 2016; Kiggundu et al., 2018). The Soil and Water Assessment Tool (SWAT) (Arnold et al., 2013) is one of these tools which has been fruitfully applied at the catchment scale to evaluate the impact of land use management on water resources. The SWAT model application for assessing LULC change impacts on water resources has gained momentum in the world (Mango et al., 2011; Lam et al., 2011; Yevenes and Mannaerts, 2011; Brown and Sutcliffe, 2013; Feng et al., 2013; Memarian et al., 2014; Danvi et al., 2018). The applicability and efficiency of SWAT in hydrological simulation of tropical catchments has been approved. As an example, Githui et al. (2009) estimated the impact of land cover change on runoff in a tropical catchment in Kenya by coupling SWAT and the Conversion of Land use and its Effects at Small regional extent (CLUE-S) model. That study provided useful insights into the sensitivity of catchment hydrological systems attributable to LULC change.

Further, in the East African region, a significant number of studies have been conducted to improve the knowledge of LULC change impacts on water resources at local and regional scales (Kimwaga et al., 2012; Anaba et al., 2017; Guzha et al., 2018). Admittedly, a limited

number of studies (e.g. Böhme et al., 2016) have assessed the impact of LULC change on the water resources of inland valleys through hydrological modelling. In this region where wetlands are undergoing drastic land use management changes, there is a tremendous need to invest in more research on understanding the impact of the changing land use management on these valuable and vulnerable ecosystems. Therefore, the overriding goal of the study is to improve the understanding of the feedback between land use management and hydrology in order to assist sustainable water resources management at a wetland - catchment scale. Specifically, the study has the following objectives i) to set up two hydrological models with different spatial discretization, i.e. the hydrological response unit (HRU)-based interface (ArcSWAT) and the grid-based interface (SWATgrid) suitable for land use management impact assessment at the wetland-catchment scale and ii) to analyse the impact of land use management practice on the stream discharge and water balance components of a tropical inland valley catchment.

2. Materials and methods

2.1. Study area

The investigated inland valley in Namulonge is situated in the Lake Kyoga basin and covers an area of 31.1 km^2. The catchment lies between latitude 0° 30′–0° 34′N and longitude 32° 34′–32° 40′E, 30 km north of Kampala in Wakiso district, central Uganda (Fig. 1). The topography is described by an undulating landscape, where gentle, wavy slopes alternate with wetlands in the shallow valley bottoms (Myamoto et al., 2012). The main stream of the inland valley drains into Lake Kyoga through the Ssezibwa River. The Lake Kyoga basin is characterized by a dense network of diverse wetlands with abundant surface and groundwater resources. However, the wetland resources are continuously degraded due to land use changes, specifically agriculture (Ministry of Water and Environment, 2010). The native vegetation of the inland valley is papyrus (*Cyperus papyrus L*) and tropical rainforests but has been significantly reduced by human activities. For example, intensive subsistence agriculture with a mosaic of land use types and management has increased in the inland valley (Gabiri et al., 2018).

The area is characterized by tropical climate with an average annual rainfall of 1200 mm. Rainfall is bimodally distributed with the first and longer rainy season occurring between March and June and a second, shorter rainy season between August and November. The average annual temperature is 22 °C (Nsubuga, 2000). The valleys are filled with quaternary sediments, which are described as alluvium, swamps, and lacustrine deposits (GTK Consortium, 2012). The slopes of the inland valley are comprised of undifferentiated Nitisols (Jones et al., 2013), which show a deep red color with a well-developed nut-shaped structure, suitable for the cultivation of a wide range of crops. The major soil types include rhodic Nitisols on the upper hills of the catchment as well as umbric Gleysols, gleyic Fluvisols, and Histosols in the valley bottom.

On the slopes of the inland valley, upland food crops such as maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), and sweet potatoes (*Ipomoea batatas* L.) are cultivated. In the valley bottom, intensive subsistence agriculture with a mosaic of land use types exists, which include (*Oryza sativa* L.), taro (*Colocasia esculenta* [L.] Schott) cultivated under saturated or near-saturated conditions, and upland crops mentioned above and vegetables are grown on raised ridges (Gabiri et al., 2018).

2.2. Hydrological modelling

In this study, the ArcSWAT 2012 interface (Arnold et al., 2013) was applied to set up the SWAT model, to assess the hydrological characteristics of the inland valley catchment. Additionally, SWATgrid, a user interface for SWAT, with a gridded discretization scheme (Rathjens et al., 2014), was set up to explicitly consider exchange of water and matter fluxes between the simulation units which is missing in the Hydrological Response Unit (HRU) approach.

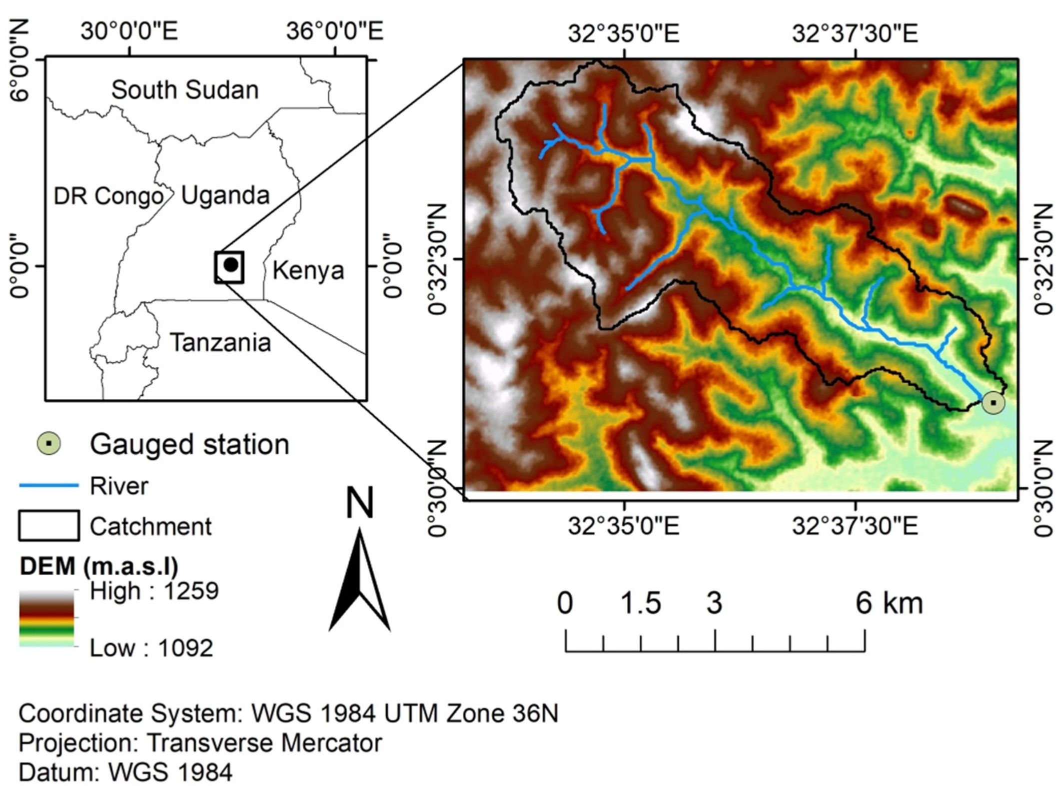

Fig. 1. Location of study area.

The SWAT model is a physically based, semi-distributed catchment model for continuous simulation of water quantity and quality on a daily basis (Neitsch et al., 2011; Arnold et al., 2012). The catchment is partitioned into sub-catchments, generated from drainage patterns derived from the topographic information. The sub-catchments are further discretized into HRUs, consisting of unique combinations of soils, LULC and slope classes (Arnold et al., 2013). The model is partitioned into land phase and channel processes. For the land phase, the hydrological processes are simulated at HRU level and aggregated for each sub catchment to calculate the overall water balance with the integration of climate data and channel processes (Neitsch et al., 2011). Surface runoff, lateral flow, groundwater recharge, infiltration, evapotranspiration, and groundwater flow are the main processes simulated by the model. Detailed descriptions of the model and how the different processes are simulated can be found in Arnold et al. (1998) and Neitsch et al. (2011).

The grid-based version of SWAT (SWATgrid) in its current version is not a standalone application, therefore, requires a running HRU version (Rathjens and Oppelt, 2012a). Results from ArcSWAT and the TOPographic PArametriZation tool (TOPAZ) (Garbrecht et al., 2000) are used to derive flow paths from the digital elevation model (DEM). Hence, calibrated and validated ArcSWAT files were used to run SWATgrid in this study. Surface runoff, lateral and groundwater flow processes are individually computed in SWATgrid for each grid before being routed to one of the eight adjacent cells (Pignotti et al., 2017). Unlike the constant flow separation ratio used in ArcSWAT (Arnold et al., 2010), the spatial distribution of flow separation in the SWATgrid is controlled by a drainage density factor (Rathjens et al., 2014).

2.3. Model input data

Table 1 shows the data used to set up the SWAT model. A 30 m spatial resolution digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) (data available from the U.S. Geological Survey - earthexplorer.usgs.gov) was used to derive the topographic information. At the beginning of the study, detailed spatial information on the distribution of land use and land cover, soil types, soil physical and chemical properties was missing. Thus, soil, and land use and land cover maps with their related attributes had to be developed.

2.3.1. Soil and land use data

A soil map indicating the spatial distribution of the major soil types and their properties in the catchment was developed based on the FAO approach (FAO, 2006). The approach involved use of a topographic map at a scale of 1:20,000 (with a 2 m contour interval), aerial imagery (Google Earth map) to delineate major land form units, detailed soil profile descriptions and soil sampling for physical and chemical properties' analysis, and extrapolation and delineation of soil boundaries. Soil boundaries were established and assessed by auger method to approximately 120 cm soil depth. Major soil types were identified, mapped using a handheld global positioning system (GPS), and described in detail according to FAO (2006). Soil parameters such as particle-size distribution, bulk density, pH, electrical conductivity, soil organic carbon, exchangeable bases, and cation exchange capacity from soil profiles for the major soil units were analyzed at soil science laboratory, Makerere University, Kampala, Uganda. The interpolation of soil boundaries between adjacent pits, auger points were made through analysis of topographic and vegetation boundaries as derived from the Google Earth images. Field classification and delineation of soil boundaries were based on key intrinsic soil properties as described in WRB (2014). Based on the laboratory data, field classifications were updated and the soil map completed.

The LULC map for the study area was developed from Sentinel-2 images of 2016 with 10 m spatial resolution (Drusch et al., 2012). To enhance the accuracy of the land use classification, training data were systematically collected for each land use class using a handheld GPS. A total of 450 observation points were collected during the months of November 2015 and February 2016. Based on the training data, a random forest classifier with 1000 trees (Breiman, 2001) was used to classify the different land use types.

2.3.2. Monitoring data

Stream discharge and climatic data measurements were conducted for calibration and validation of the models during the hydrological years of 2015 and 2016, respectively. Stream water level was measured every 15 min using a YSI 6- series multiparameter water quality sonde (YSI Incoporated, 2010) installed at the catchment outlet. Several instantaneous discharge measurements were conducted using an acoustic digital current meter (ADC, OTT Hydromet GmbH) consistently with the recommendations after Fenton and Keller (2001) at the catchment outlet, to establish the relationship between stream water level and discharge. Climate data, including precipitation, temperature, relative humidity, wind speed and solar radiation were obtained from the National Crops Resources Research Institute (NaCRRI) automatic weather station database.

2.4. Model setup

2.4.1. ArcSWAT setup and calibration

The initial model setup was carried out with the ArcSWAT 2012 (revision 664) using a 30 m DEM. A total of 27 sub-catchments were defined with 174 HRUs from a unique combination of land use, soil type and slope, at thresholds over the sub-catchment area of 15%, 10% and 10%, respectively. Surface runoff and infiltration were computed using the Soil Conservation Services (SCS) curve number method (SCS, 1972). Evapotranspiration was calculated based on the Penman-Monteith method (Monteith and Moss, 1977), using the observed climate data. Lateral flow was calculated using a kinematic storage model described in Arnold et al. (1998).

After the initial setup, the model was calibrated and validated at a daily resolution using Sequential Uncertainty Fitting (SUFI-2) algorithm in the SWAT Calibration and Uncertainty Program (SWAT-CUP, version 5.1.6.2) (Arnold et al., 2012), following the procedures of Abbaspour et al. (2015). The SUFI-2 program was applied for parameter optimization and Latin Hypercube sampling iteratively discarded the worst simulations by rejecting the 2.5th and 97.5th percentile of the cumulative distribution. Thus, the best 95% of simulations generated a parameter range (95% prediction uncertainty, 95PPU) rather than a single final parameterization. The uncertainty band (95PPU) was used to account for the modelling uncertainty (Arnold et al., 2012).

2.4.2. SWATgrid setup

The SWATgrid version uses the calibrated ArcSWAT parameter sets and no further calibration is carried out. Therefore, the calibrated

Table 1
Spatial data used for the SWAT model.

Data set	Resolution/scale	Source	Data description and usage
Topography	30 m	SRTM	Digital Elevation Model (DEM)
Soil	1:20,000	Soil survey	Soil physical properties
Land use	10 m	Own representation	Land use classification based on Sentinel-2 image and field data
Climate	Daily, 1 station	Namulonge automatic weather station	Solar radiation, wind speed, rainfall, temperature, and relative humidity (1 Jan 2015 to 31 Dec 2016)

parameter sets remained unchanged except for the discretization scheme, and the drainage density factor which was manually adjusted (Duku et al., 2015). In line with the resolution of the DEM used in ArcSWAT, SWATgrid discretized the catchment into 33,687 grid cells each at 30 m resolution. Compared to ArcSWAT, the discretization scheme of SWATgrid provides better spatially detailed information for land use and soil data. Also, a more accurate estimation of the water balance is expected at a catchment scale, due to the ability of SWATgrid to account for lateral fluxes between the grid cells (Rathjens et al., 2014). To ensure comparison of the two models, the SWATgrid was applied for the same time period as ArcSWAT. Because of the nearly 200 times more simulation units, the computation time for SWATgrid increased from 5 min to 27 h using a 2.7 GHz computer.

2.5. Model evaluation

In this study, the model performance during calibration and validation was evaluated based on four quantitative statistics, specifically, the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), the Kling-Gupta efficiency (KGE) (Gupta et al., 2009) and the percent bias (PBIAS) (Gupta et al., 1999). The coefficient of determination (R^2) ranges between 0 and 1.0, with high values indicating less error variance (Rathjens and Oppelt, 2012a). The NSE which was used as the objective function ranges between -∞ and 1.0. An NSE of 1.0 indicates a perfect fit between the simulated and observed data (Moriasi et al., 2007). The optimal value of PBIAS is 0%, with positive and negative values indicating model

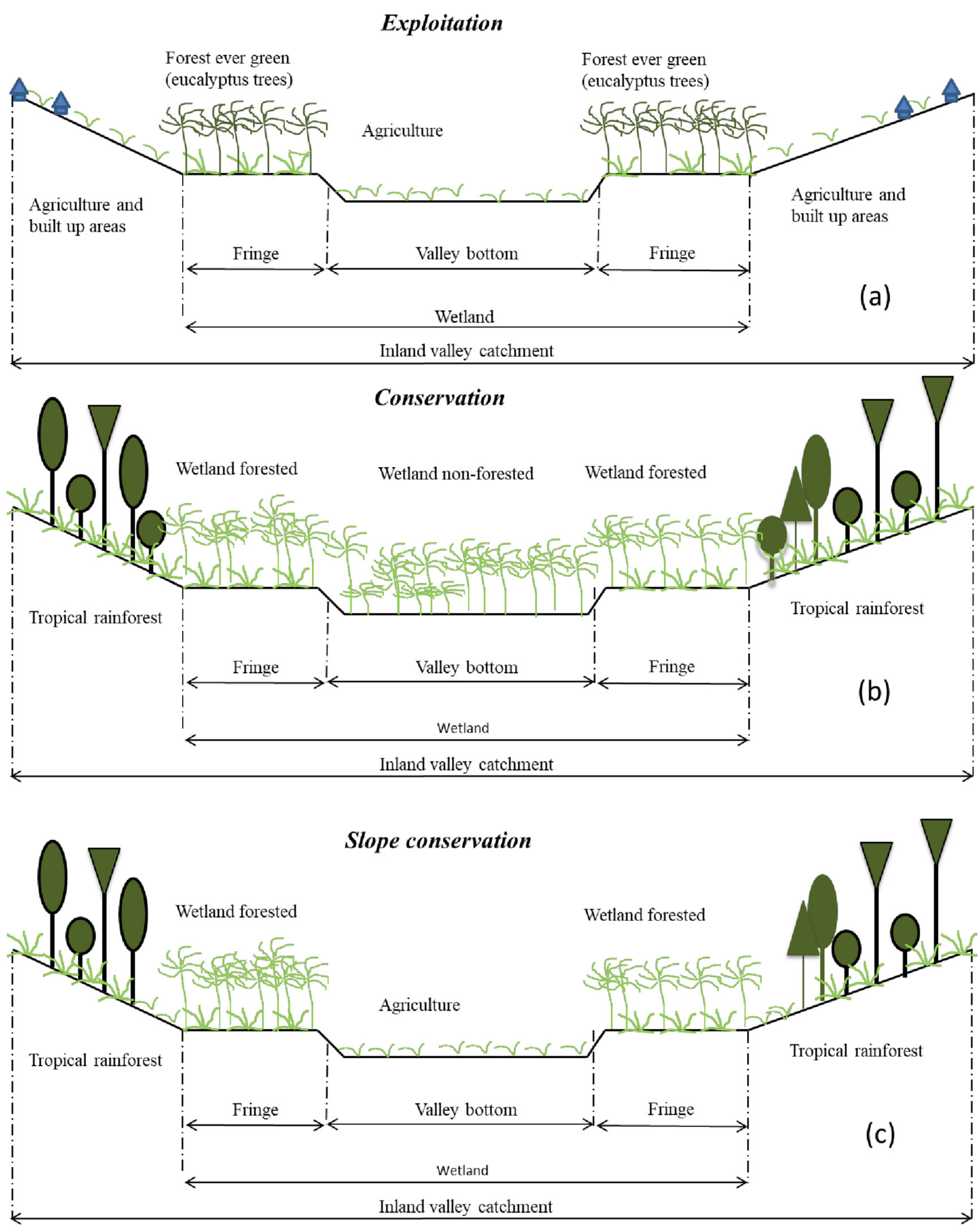

Fig. 2. Schematic illustration of land use management options in the inland valley catchment.

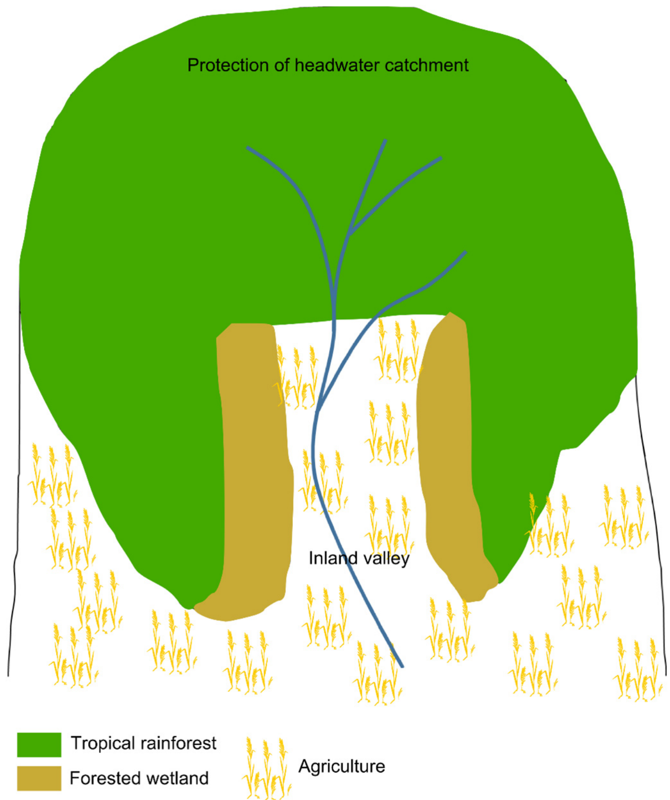

Fig. 3. Schematic illustration for the land use management option *Protection of the headwater catchment*.

underestimation and overestimation bias, respectively (Gupta et al., 1999). The model performance was considered to be satisfactory if NSE > 0.50, R^2 > 0.50, PBIAS ±25% (Moriasi et al., 2007) and KGE > 0.5 (Kling et al., 2012).

The modelling uncertainty was quantified as the *P*- and *R*-factor (Arnold et al., 2012). The P-factor measures the ability of the model to bracket the observed data with the 95PPU. The P-factor is between 0 and 1, where 1 means a 100% bracketing of the observed data. The R-factor represents the width of the 95PPU, ranges from 0 to ∞ and should be below 1, implying a small uncertainty band (Arnold et al., 2012).

2.6. Land use management

The impact of land use management options on the water balance of the inland valley catchment was evaluated after validation of the SWAT model. Hypothetical land use management options were developed and explored in addition to the reference land use map of 2015 applied for calibration and validation. The land use management options were derived due to lack of a series of detailed land use maps at the scale of the study area for the past years, which would allow analysis of land use and land cover changes over time and how these changes have impacted on the inland valley's hydrology. The development of the land use management options were in accordance with the ongoing trends of land use change and with management efforts within the study area and across the East African region for the inland valleys. Therefore, we adopted the functional landscape approach (FLA) described by Dixon et al. (2012) in the development of these land use management options. The FLA recognizes the wetland –catchment linkage to achieve sustainable wetland use and water resource management (Wood et al., 2013). The land use management options included; 1. *Exploitation:* This option involved total conversion of the valley bottom of the wetland into agriculture, the wetland fringes to forest evergreen (FRSE) like eucalyptus trees and the catchment slopes into agriculture and residential areas (Fig. 2a). This option represents the ongoing land use change and management trend within the study area and the region. Exploitative land use has been reported as one of the major causes of inland valley catchment degradation in the region (Uganda wetland atlas, 2016). 2. *Conservation*: Complete conversion of the inland valley catchment into its natural state. The option involved total conversion of the wetland valley bottom into wetland non-forested (natural papyrus), a typical characteristic of the tropical wetlands in the region (Okeyo-Owuor and Raburu, 2016), wetland fringe into wetland forested and catchment slopes into tropical rainforest (mixed forest) (Fig. 2b). 3. *Slope conservation:* This option involved conversion of the valley bottom and lower slopes into agriculture, wetland fringes into wetland forested and the upper catchment slopes into tropical rainforest (mixed forest) (Fig. 2c). 4. *Protection of the headwater catchment:* This option was adopted from the Rwanda Environmental Management Authority (REMA) wetland - catchment conservation approach (unpublished). It involved total protection of the headwater catchment with tropical forests (mixed forest; FRST) while at the lower catchment, the valley bottom was converted into agriculture, wetland fringes into forested wetlands and the catchment slopes into tropical rainforests (mixed forest; FRST) (Fig. 3). The land use proportions in the inland valley catchment after implementation of the hypothetical land use management options are shown in Table 2.

3. Results

3.1. Soil and land use data

The distribution of the soil types in the inland valley are presented in Fig. 4. The inland valley is characterized by five soil types with prefix qualifiers added to the name of reference soil group according to WRB (2014). These include Eutic rhodic Nitisols (62.2%) on the upper slopes of the catchment, Eutic rhodic Nitisols (colluvic), (23.4%) along the slopes, Eutic umbric Gleysols (10.3%) predominant in the valley bottom and fringes, Eutic Gleyic Fluvisols (4.0%) mainly observed at the tributaries of the main stream, and Eutic Gleyic Arenosols (0.1%) along the fringes.

Fig. 5. shows the developed land use and land cover of the inland valley catchment. A total of six LULC classes were classified, including agriculture, mixed forest (tropical rainforest), evergreen forest (plantations

Table 2
Land use proportion (in %) according to land use management options.

Land use type	Reference	Exploitation	Conservation	Slope conservation	Protection of the headwater catchment
Agriculture (AGRL)	64.1	79.2	–	7.14	26.49
Forest evergreen (FRSE)	11.6	7.2	–	–	–
Mixed forest (FRST)	11.8	–	85.69	85.69	69.70
Wetland non-forested (WETN)	–	–	7.14	–	–
Wetland forested (WETF)	–	–	7.18	7.18	3.82
Built - up areas (URLD)	2.2	13.6	–	–	–
Water (WATR)	1.3	–	–	–	–
Pasture (PAST)	9.0	–	–	–	–

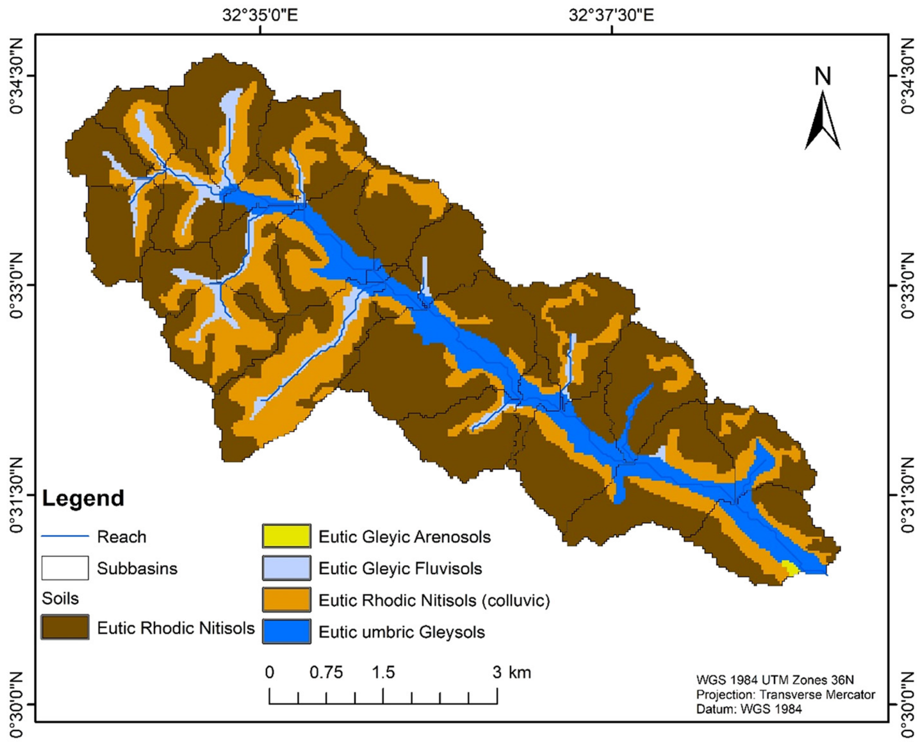

Fig. 4. Distribution of soils in the study area.

of e.g. eucalyptus), pasture, urban, low density, and water. The predominant land use/cover classes include agriculture with a coverage of 64.8% of the total catchment area, mixed forest (tropical rainforest, 11.8%), and evergreen forests, 11.7% of the total catchment area. The spatial pattern of land use is very spotty and shows agricultural use as well as pasture next to one another, because the inland valley is mainly cultivated by smallholder farmers.

3.2. Model performance comparisons

Fig. 6. presents the comparisons between the simulated and observed discharge (Q) from the ArcSWAT and SWATgrid model setups for the year 2015 and 2016 at the catchment outlet. Good accordance between the simulated and observed discharge was noticed albeit some peaks are overestimated by both model setups. The

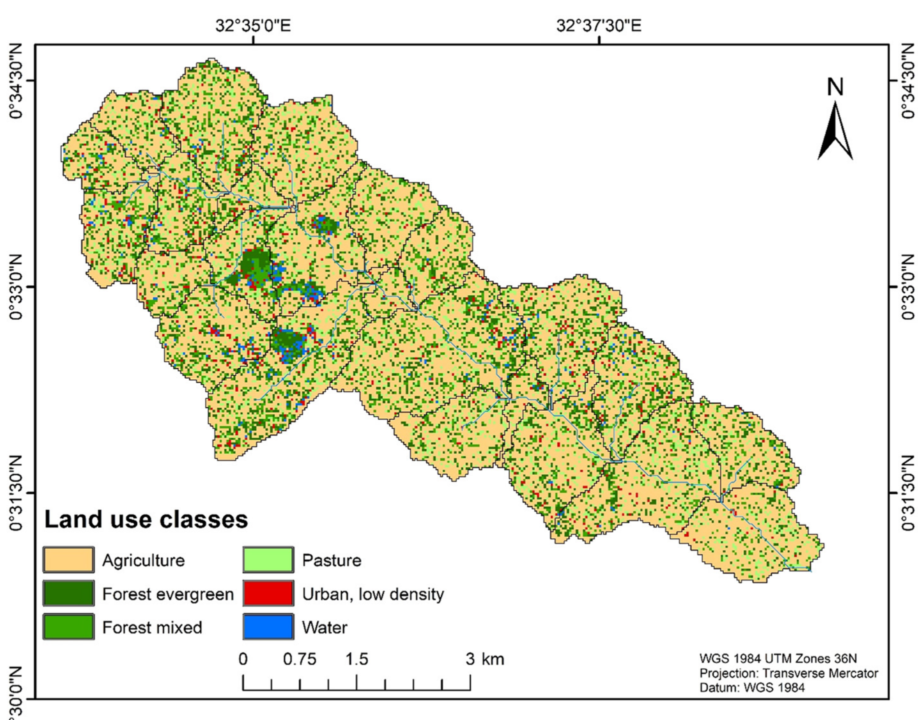

Fig. 5. LULC classification used in the study.

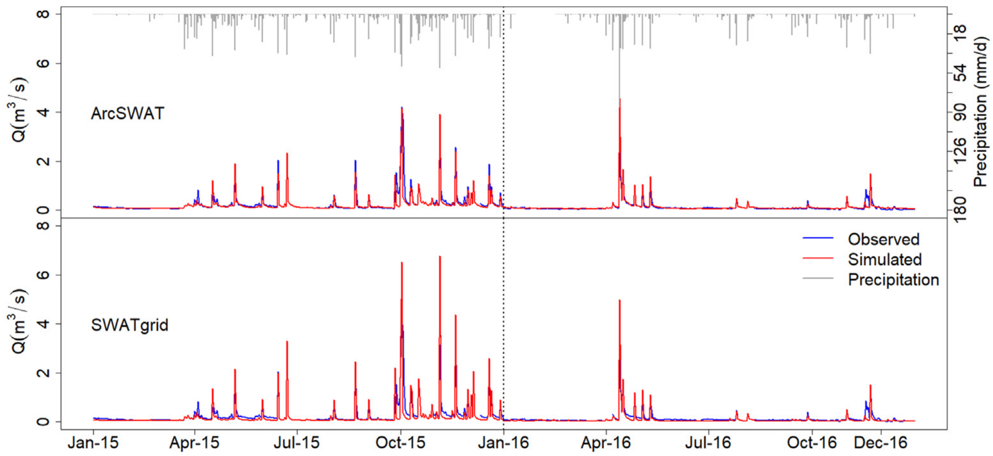

Fig. 6. Observed and simulated discharges for the calibration (2015) and validation (2016) periods at the catchment outlet from the two model setups (quality measures see Table 3).

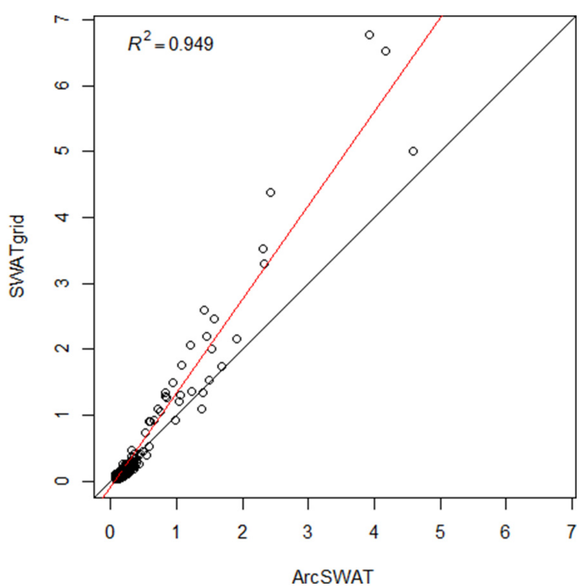

Fig. 7. Correlation between simulated discharge [m^3/s] from ArcSWAT and SWATgrid model setups.

misrepresentation of peak flows can be explained by measurement errors as result of overbank flow which was often observed at the gauging station, due to the small size and depth of the stream and the management practices along the channel, which hindered the natural flow pattern of the stream. SWATgrid simulated higher peak flows than ArcSWAT setup, however, the simulated daily discharge derived from the two model setups matched very well ($R^2 = 0.95$) (Fig. 7).

Table 3 shows the model performance measures for the calibration and validation of ArcSWAT and SWATgrid. The performance of ArcSWAT is considered to be acceptable for the discharge calibration and validation. The statistical indicators (R^2, NSE, and KGE) were >0.5. PBIAS indicator showed positive values signifying underestimation of discharge by the model during calibration. However, an overestimation of discharge with a negative PBIAS was seen during validation. The goodness of fit and degree to which the calibrated model accounts for the parameter uncertainty in SUFI-2 algorithm is assessed by the p-factor and r-factor. The p-factor is the percentage of observed data falling into the 95% prediction uncertainty (95PPU) band. The r-factor is the thickness of the 95PPU envelop (Abbaspour, 2015). The p-factor values indicated that 84% of the observed discharge data was enveloped by the model. The r-factor reached an acceptable value of 0.27 during the calibration period. Although, the model exhibited some uncertainties in the simulation of low and peak discharge, the p-factor and r-factor reveal that the simulated discharge fit to the observed data.

Likewise, for the SWATgrid model setup, the model quality measures were satisfactorily achieved, especially during the calibration period. In comparison with the ArcSWAT model, SWATgrid performed equally well in the prediction of discharge at the catchment outlet. The R^2, NSE, KGE were above 0.50 while the PBIAS indicator showed an underestimation of discharge by the model.

3.3. Comparison of annual water balance from ArcSWAT and SWATgrid models in the inland valley

A comparison of the simulated mean annual water balance of the ArcSWAT and SWATgrid model setups is provided in Table 4.

Results of ArcSWAT and SWATgrid show that water from precipitation is predominantly lost via evapotranspiration in the inland valley catchment at ratios of 65.0% and 69.0%, respectively. Deep aquifer recharge accounts for 13.3% from ArcSWAT and 10.9% from SWATgrid of the total precipitation received in the catchment. The surface runoff and evapotranspiration calculated by SWATgrid are 60.5 mm, and 43.7 mm, respectively more than that from ArcSWAT. However, ArcSWAT compensates this effect by higher amounts of lateral flow (23.9 mm), groundwater flow (13.6 mm), and deep aquifer recharge (30.6 mm). Total water yield simulated by SWATgrid was 23.0 mm higher than that from ArcSWAT. This is due to the higher surface runoff exhibited by SWATgrid than ArcSWAT. For both model setups, the simulated total water yield is lower than the observed in the inland valley catchment. Runoff contributes more to stream discharge than groundwater flow in the inland valley catchment. In detail, for ArcSWAT, 12.7% of the precipitation is converted to stream discharge (6.0% surface runoff and 6.7% lateral flow), and 5.5% of precipitation contributes to

Table 3
ArcSWAT and SWATgrid model performance indicators for discharge at the catchment outlet.

Model set up	Calibration						Validation					
	p-factor	r-factor	R^2	NSE	KGE	PBIAS [%]	p-factor	r-factor	R^2	NSE	KGE	PBIAS [%]
ArcSWAT	0.84	0.27	0.75	0.73	0.72	16.0	0.70	0.34	0.80	0.69	0.65	−8.1
SWATgrid	–	–	0.69	0.51	0.64	19.1	–	–	0.80	0.50	0.50	23.5

Table 4
Mean annual water balance components simulated by SWATgrid and ArcSWAT.

Water balance components	ArcSWAT	SWATgrid	Diff.
Precipitation [mma^{-1}]	1300.0	1300.0	0.0
Surface runoff [mma^{-1}]	77.9 (6.0%)	138.4 (10.6%)	60.5
Lateral flow [mma^{-1}]	86.5 (6.7%)	62.6 (4.8%)	−23.9
Groundwater flow [mma^{-1}]	72.1(5.5%)	58.5 (4.5%)	−13.6
Water yield [mma^{-1}] (284.8 mma^{-1} observed water yield)	236.5 (18.2%)	259.5 (20.0%)	23.0
Deep aquifer recharge [mma^{-1}]	172.6 (13.3%)	142.0 (10.9)	−30.6
Actual evapotranspiration [mma^{-1}]	849.5 (65.0%)	893.2 (69.0%)	43.7
Potential evapotranspiration [mma^{-1}]	1157.4	1170.5	13.1

Note: Percentage value in brackets is a component ratio to precipitation.

groundwater flow. For SWATgrid 15.4% of the precipitation (10.6% surface runoff and 4.8% lateral flow) is converted to stream discharge while 4.5% of precipitation is transformed into groundwater flow (Table 4). Despite the differences in the magnitude of the simulated hydrological processes, the two model setups show similar trends of the dominant processes in the inland valley catchment.

3.4. Effect of land use management on water quantity in the inland valley catchment

The comparison of the simulated annual water balance for the year 2015 with respect to the model setups and the applied land use management options gives a general overview on the impact of LULC change on the hydrological performance of the studied inland valley. Tables 5 and 6 and Fig. 8 documents the annual water balances for the two model setups after application of the different land use management options.

For ArcSWAT, a decrease in the total annual discharge (surface runoff, lateral and groundwater flow) among the land use management options is simulated following the order *Conservation*, *Slope conservation*, *Protection of head water catchment*, and *Exploitation* (Table 5). More explicitly, *Conservation* led to a decrease of 68.7 mm in surface runoff, followed by *Slope conservation* (67.1 mm), *Protection of headwater catchment* (40.5 mm) and *Exploitation* (3.9 mm) from the reference land use. An increment of annual actual evapotranspiration from the reference was exhibited by the different land use management options e.g. 16.0%, (from *Conservation*), 15.0% (from *Slope conservation*), 8.0% (from *Protection of headwater catchment*) and 1.0% (from *Exploitation*) (Fig. 8a). This implies that if conservation management is considered, more water is stored in the vegetation and lost through transpiration. Furthermore, land use management change led to a decrease in the total water yield of 44.0%, 42.0%, 27.0%, and 1.0% for the *Conservation*, *Slope conservation*, *Protection of headwater catchment* and *Exploitation* options, respectively (Fig. 8a). Deep aquifer recharge showed a decreasing trend from the reference among the land use management options following the order *Conservation* < *Slope conservation* < *Protection of the headwater catchment* < *Exploitation*.

With regard to the SWATgrid model setup, Table 6 shows a significant decrease in the total annual discharge (surface runoff, lateral flow and groundwater flow) among the land use options following the order *Conservation* < *Slope conservation* < *Protection of the headwater catchment* < *Exploitation*. Contrary to ArcSWAT, *Exploitation* exhibits a significant increase in surface runoff of 31.2 mm from the reference for the SWATgrid model. Additionally, a decrease in lateral flow (8.7 mm) and ground water flow (4.6 mm) from the *reference* due to *Exploitation* land use was noted. An increment in lateral and groundwater flow was observed from the *Conservation*, *Slope conservation* and *Protection of the headwater catchment*. A decrease of 26.0%, 24.0%, and 16.0% in annual water yield was simulated for *Conservation*, *Slope conservation* and *Protection of the headwater catchment*, respectively, while an increase of 7.0% was noted from the *Exploitation* land use (Fig. 8b).

Likewise, there was an increase in the actual evapotranspiration for the applied land use management options except for the *Exploitation* land use (Table 6, Fig. 8b). Actual evapotranspiration from *Conservation* increased by 100.8 mm more than that from *Reference*. *Slope conservation* had 94.8 mm and *Protection of the headwater catchment*, 34.1 mm

Table 5
Changes in water balance according to land use scenarios simulated using ArcSWAT. Deviations [mm] from the reference are shown in brackets.

Water balance components	Reference	Exploitation	Protection of headwater catchment	Conservation	Slope conservation
Precipitation [mma^{-1}]	1300.0	1300.0	1300.0	1300.0	1300.0
Surface runoff [mma^{-1}]	77.9	74 (−3.9)	37.4 (−40.5)	9.2 (−68.7)	10.8 (−67.1)
Lateral flow [mma^{-1}]	86.5	92.6 (6.1)	82.1 (−4.4)	79.5 (−7.0)	80.2 (−6.3)
Groundwater flow [mma^{-1}]	72.1	68.3 (−3.8)	52.4 (−19.7)	44.0 (−28.1)	46 (−26.1)
Water yield [mma^{-1}]	236.4	234.9 (−1.5)	171.9 (−64.5)	132.7 (−103.7)	137 (−99.4)
Deep aquifer recharge [mma^{-1}]	172.6	164.4 (−8.2)	128.4 (−44.2)	103.7 (−68.9)	108.4 (−64.2)
Actual evapotranspiration [mma^{-1}]	849.5	856.5 (7.0)	919.2 (69.7)	986.6 (137.1)	975.1 (125.6)
Potential evapotranspiration [mma^{-1}]	1157.4	1157.4	1157.4	1157.4	1157.4

Table 6
Changes in water balance according to land use scenarios simulated using SWATgrid. Deviations [mm] from the reference are shown in brackets.

Water balance components	Reference	Exploitation	Protection of headwater catchment	Conservation	Slope conservation
Precipitation [mma^{-1}]	1300.0	1300.0	1300.0	1300.0	1300.0
Surface runoff [mma^{-1}]	138.4	169.6 (31.2)	50.8 (−87.6)	5.9 (−132.5)	11.7 (−126.7)
Lateral flow [mma^{-1}]	62.6	53.9 (−8.7)	90.8 (28.2)	102.8 (40.2)	102.8 (40.2)
Groundwater flow [mma^{-1}]	58.5	53.9 (−4.6)	77.1 (18.6)	83.6 (25.1)	83.8 (25.3)
Water yield [mma^{-1}]	259.4	277.4 (18)	218.7 (−40.7)	192.3 (−67.1)	198.3 (−61.1)
Deep aquifer recharge [mma^{-1}]	142.0	132.0 (−10)	142.3 (0.3)	102.1 (−39.9)	103 (−39)
Actual evapotranspiration [mma^{-1}]	893.2	883.7 (−9.5)	927.3 (34.1)	994.0 (100.8)	988.0 (94.8)
Potential evapotranspiration [mma^{-1}]	1170.5	1170.5	1170.5	1170.5	1170.5

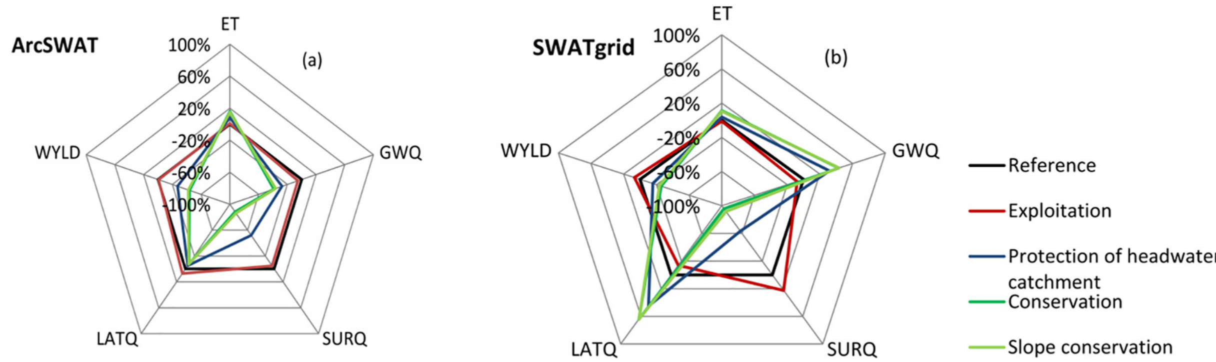

Fig. 8. Percentage change in water balance. ET; Actual evapotranspiration, WYLD; Water yield, LATQ; Lateral flow, SURQ; Surface runoff, GWQ; Groundwater flow.

more actual evapotranspiration than that from *Reference*. A decrease of 9.5 mm actual evapotranspiration due to *Exploitation* was noted (Table 6). A decline in deep aquifer recharge was generally observed among the different land use management options. In summary, both model setups showed similar behaviour in the simulation of the water balance components although there were differences in the magnitude.

The main advantage of the SWATgrid setup is its explicit consideration of spatial patterns (Pignotti et al., 2017). Therefore, spatial patterns of runoff (lateral flow and surface runoff) were analyzed from the SWATgrid. The spatial patterns of these fluxes show the impact of topography, landscape position, and land use and soil types on the model output.

Fig. 9 shows that lateral flow (LATQ) values are highest at the steep slopes, and almost no lateral flow occurs in the valley bottom which is an expected pattern. Topography, soil properties, and land use management are the main factors determining the amount of LATQ. Steep slopes allow lateral flow while in flat areas the water will percolate towards the shallow aquifer. LATQ increases among the land use management options following the order: *Conservation* > *Slope conservation* > *Protection of the headwater catchment*. This can be explained by the increased mixed forest proportions in the same order along the slopes which encourage infiltration.

The SWATgrid model simulates higher runoff at the upslope than in the valley bottom and in the grid cells with Fluvisols for the *Reference* and *Exploitation* (Fig. 10). This can be explained by the increased percentage of agricultural land use and built-up areas (urban, low density) together with the steep slopes, which lower the infiltration rate inducing surface runoff. Contrary to the *Exploitation*, the upslope grid cells under *Conservation*, *Slope conservation* and *Protection of the headwater catchment* exhibit lower surface runoff than the valley bottoms. The low surface runoff at the upslope can be attributed to the high percentage of mixed forest land use which increases the infiltration rate,

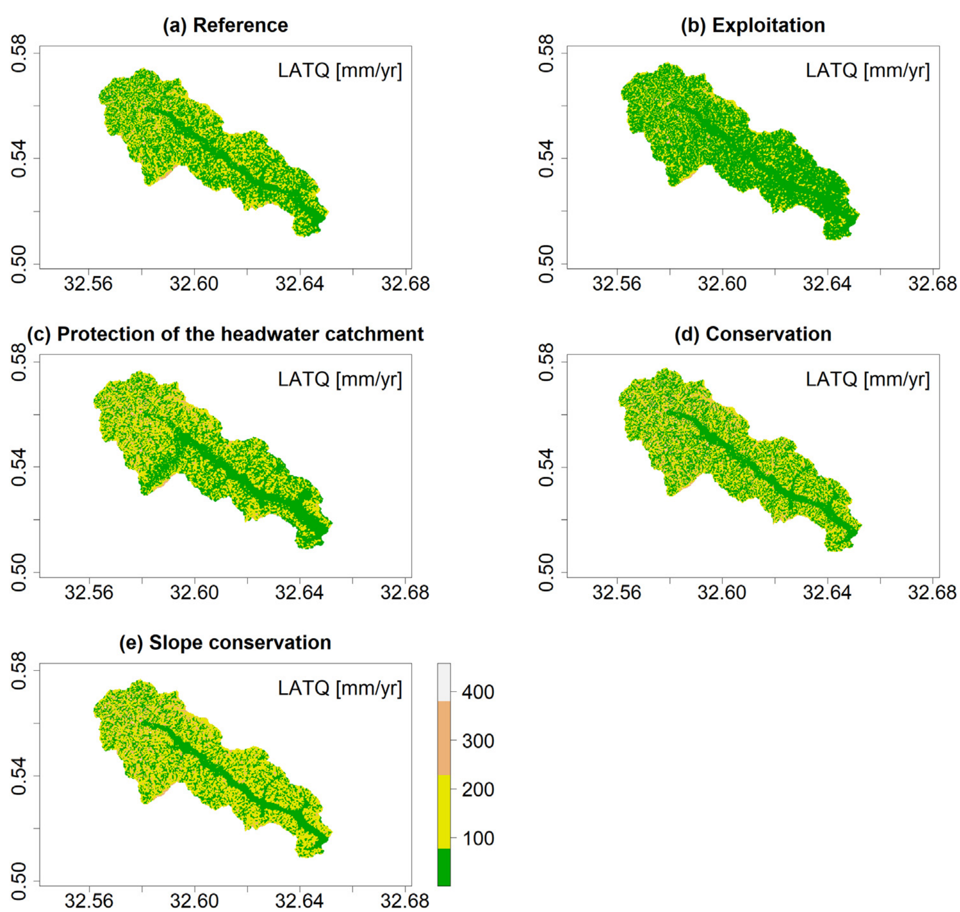

Fig. 9. Spatially explicit distribution of lateral flow (LATQ) for the different land use management options simulated by SWATgrid.

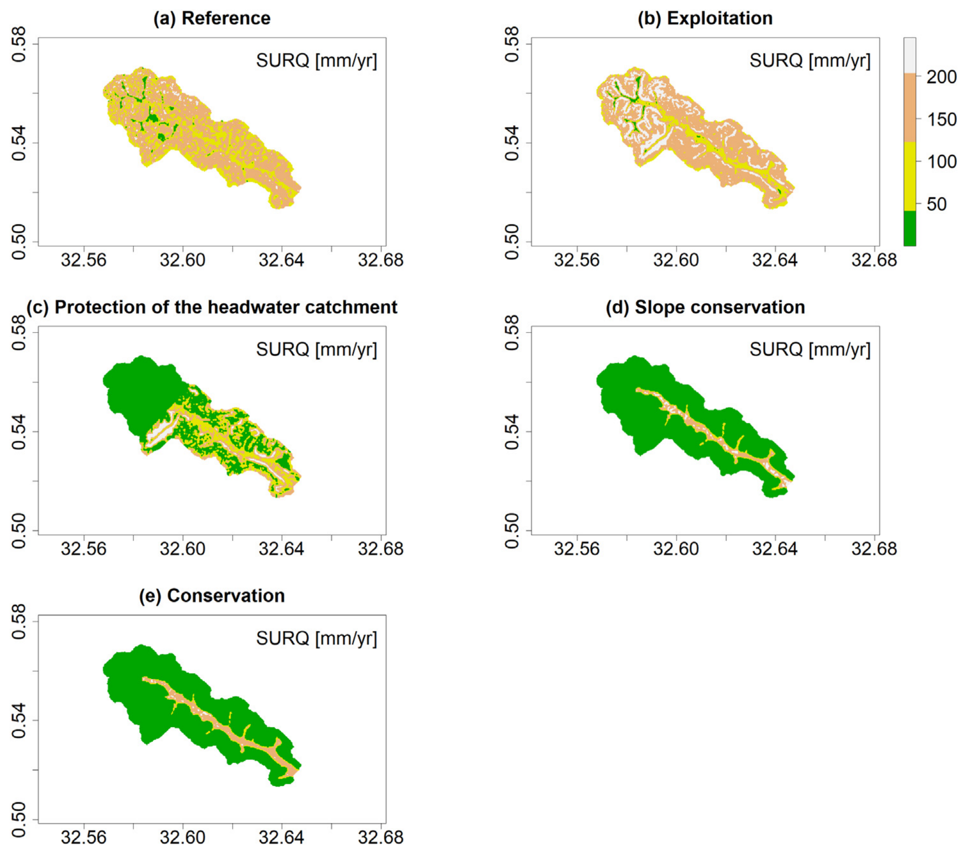

Fig. 10. Spatially explicit distribution of surface runoff (SURQ) for the different land use management options simulated by SWATgrid.

resulting into increased subsurface flow. Land use management options and slope play an important role in controlling surface runoff in the inland valley catchment. For example, *Protection of the headwater catchment* shows higher runoff at the wetland fringes than the valley bottom (under the agricultural land use). This is due to the slope effect while for the *slope conservation* land use management, the valley bottom exhibits higher runoff than the fringe mainly because of the agricultural land use implemented (Fig. 10). From the spatial analysis, the SWATgrid setup enabled us to identify the hydrologically sensitive areas (HSAs) to land use change at a finer spatial resolution.

We applied the ArcSWAT model setup to evaluate the impact of land use management options on the exceedance probability of annual discharge for a period of 30 years (1976–2005). Historical downscaled climate data (30 years) from the Coordinated Regional Downscaling Experiment (CORDEX) Africa (Gutowski et al., 2016) was used to understand the long-term impact of land use change on annual discharge.

Fig. 11 depicts the results of the daily flow duration curve (FDC) from the different land use scenarios. All analyzed scenarios indicate increasing high and low flows within the simulated period (1976–2005). However, the slope of the daily FDC is unchanged for the simulated period.

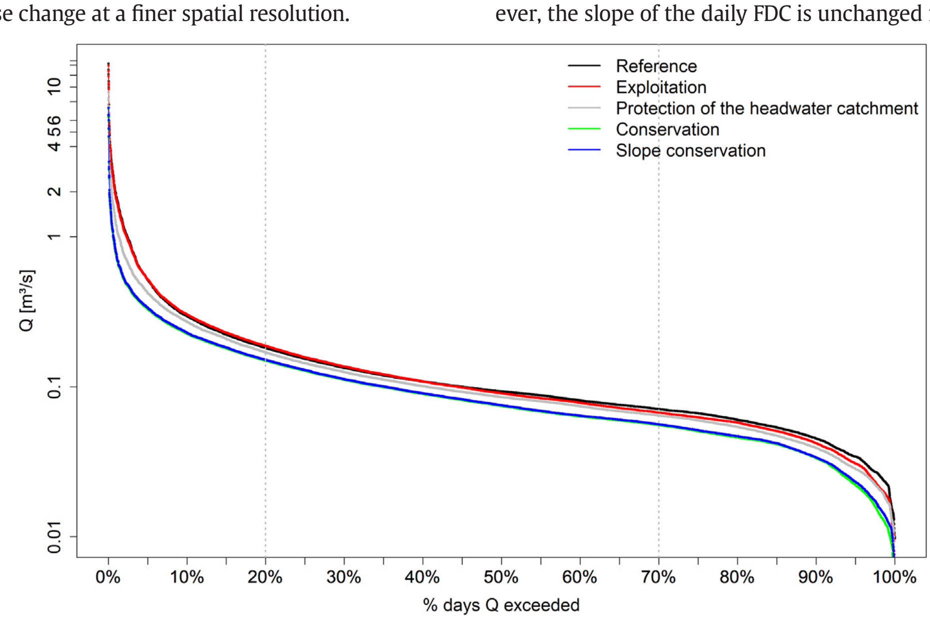

Fig. 11. Flow duration curves from ArcSWAT for the five land use management options. The y-axis is plotted on a log scale.

There are no pronounced changes observed between the *Conservation* and the *Slope conservation* land use options, although the flow duration curve for *Conservation* is lower than the *Slope conservation* FDC. Equally important, the *Exploitation* and *Reference* land use management show marginal differences for the high and low flows.

Furthermore, the FDC for the *Conservation*, *Slope conservation* and *Protection of the headwater catchment* land use options show significant decrease in high (5–10% exceedance) and increase in low (90% exceedance) flows compared to the *Exploitation* and *Reference* land use options. In general, implementation of the *Conservation* land use option as a water resources management strategy in the inland valley strongly decreases high flows followed by the *Slope conservation* and *Protection of the headwater catchment* option. These results imply that the *Exploitation* land use option encourages high flows, thus increased surface runoff and total discharge. Therefore, feasible land use management strategies (protection of the headwater catchment and slope conservation) which enhance low flows can be appropriate for water resources management in the tropical inland valleys.

4. Discussion

4.1. Hydrological modelling calibration and validation

The two model setups showed good results in the simulation of the annual discharge during the calibration and validation periods. This shows that the applied methodology by calibrating ArcSWAT using common techniques (Arnold et al., 2012; Abbaspour et al., 2015; Moriasi et al., 2007) is appropriate for running a grid-based SWAT model. Similar observations were made by Danvi et al. (2017) for three inland valleys in Benin, West Africa. This reveals that the simulated discharge is insensitive to the different discretization schemes but differs in the importance of runoff components. Specifically, the discretization scheme applied in SWATgrid resulted in increased surface runoff, water yield and actual evapotranspiration in the inland valley. The increment was to some extent compensated by higher lateral flow, groundwater flow and total aquifer recharge simulated by ArcSWAT. The discrepancies have previously been observed and discussed by Rathjens and Oppelt (2012a). The authors attribute these discrepancies in the discharge components simulations to the higher degree of details concerning the hydrological characteristics like soil type, land use and slope resolved by the SWATgrid model (Rathjens and Oppelt, 2012b).

Additionally, the differences can also emanate from the different routing concepts applied in which lateral fluxes between the grid cells are accounted for in SWATgrid, unlike ArcSWAT, by which no interaction between HRUs occurs. Indeed, according to Arnold et al. (2010), a constant flow separation ratio is applied in ArcSWAT to partition the amount of flow into landscape and channel flows. On the contrary, in SWATgrid, a spatial distribution of flows and transport processes are considered by using the modified topographic index. This index is mainly adjusted by the drainage density and applied to identify areas of high probability of runoff occurrence within the catchment (Rathjens et al., 2014).

In the inland valley, actual evapotranspiration is the dominant water loss pathway, as over 60% of the precipitation received is lost which is also supported by Danvi et al. (2017). Furthermore, runoff (surface runoff and lateral flow) is the second most important process in the study area representing about 13.0% (from ArcSWAT) and 16.0% (for SWATgrid) of the precipitation received. The high surface runoff experienced in the inland valley is a result of the land use, soil properties, and slope gradient observed in the study area. In the inland valley, agriculture (small scale agriculture with a mosaic of land uses) dominates with 64.1% area coverage. Steeper slopes prevail at the fringes and uplands of the valley. Expansions of agricultural land coupled with steeper slopes encourage overland flow due to the low infiltration rate (Burt and Slattery, 2005; Gomi et al., 2008). As a result, surface runoff and therefore, flooding risk may increase due to the on-going high level of upland-wetland cultivation.

4.2. Impact of land use management on hydrological processes

From our study, the decrease in water yield and total discharge (surface runoff, lateral flow and groundwater flow) following the land use management options (*Conservation*, *Slope conservation* and *Protection of headwater catchment*) can be attributed to the reduction in the Hortanian surface runoff. A decrease in the peak flows and increase in low flows among land use options *Conservation*, *Slope conservation* and *Protection of the headwater catchment* compared to the *Exploitation* land use and the current land use system (*Reference*) are also related to a reduction in surface runoff. Low surface runoff is induced by the increase in vegetation/canopy cover as a result of increased mixed forest (FRST; 85.7%) and wetland forested (WETF; 7.2%) coverage for both *Conservation* and *Slope conservation* land use options, and 69.7%, FRST and 3.8%, WETF for the *Protection of headwater catchment* land use option along the slopes and fringes of the inland valley. The higher the spatial coverage of mixed and wetland forested the higher the reduction in surface runoff. The trend in stream discharge and total water yield of the different land use management options was as follows: *Exploitation* > *Protection of headwater catchment* > *Slope conservation* > *Conservation*. Similar findings were documented by Li et al. (2015) who related a decrease in surface runoff to the expansion of forest land while assessing the impact of land use change on the water resources in the middle and upper reaches of the Heihe River Basin in north western China. In addition, Nugroho et al. (2013) reported a decrease in surface runoff as a result of increased forest land cover which increased interception and soil infiltration of through fall. Furthermore, a review study by Guzha et al. (2018) on the impact of land use and land cover changes on surface runoff and annual discharge in East Africa reported that loss of forest/vegetation cover led to an increase in surface runoff and peak discharge.

The impacts of land use coverage on the groundwater and lateral flow for each individual model setup is very complex. Land use cover for example agriculture may have a negative or positive effect on lateral and base flow, based on the management practices (Price, 2011). On the one hand, according to Loch (2000), increase in land coverage strongly increase infiltration rates due to improved soil porosity as a result of root activity and reduction in surface runoff, as a result increasing groundwater and lateral flow. Dense land coverage has a high potential of groundwater recharge as it is characterized by a full or partial pervious surface.

The increase in total discharge observed from the current land use system (*Reference*) and the *Exploitation* land use options can be explained by the increase in the agricultural land use in the inland valley. Leemhuis et al. (2007) attribute the increase in total discharge to the expansion of agricultural land as a result of reduced vegetation height and canopy cover. As a result, interception losses decrease resulting in a higher net precipitation that reaches the surface and thus, higher risk of surface runoff. Several authors (Githui et al., 2009; Mango et al., 2011; Yira et al., 2016; Anaba et al., 2017; Danvi et al., 2018; Näschen et al., 2018) have reported the impact of changing land use cover on the hydrologic systems of catchments, which can diversely impact the water resources at different spatial and temporal scales. In summary, the increase in the vegetation coverage among the land use management options (*Conservation* > *Slope conservation* > *Protection of headwater catchment* > *Exploitation*) generally resulted in decreased total water yield simulated from the individual model setup, as a result of increased actual evapotranspiration.

4.3. Impacts of land use management on spatial distribution of total discharge

Simulated hydrological effects for land use scenarios are fundamental to decisions aiming to optimize landscape functions (Memarian

et al., 2014). The increase in groundwater and lateral flow distribution along the slopes and wetland fringes after implementation of conservation land use scenarios was induced by the increased vegetation coverage land area (mixed forest and non-wetland forest land at the slopes and fringes, respectively) and soil types. As discussed before, increase in vegetation coverage increases water infiltration into the soils thus resulting in more subsurface flows in the catchment. On the other hand, exploitative practices (increase in agricultural land) will greatly reduce the groundwater resources and lateral flow along the catchment slopes and wetland fringes. The spatial distribution of surface runoff in the inland valley is controlled by topography, soil type and land use management options. Implementation of conservation management scenarios will greatly reduce surface runoff along the slopes and the wetland fringes of the inland valley. Additionally, conservation measures which protect the surrounding catchments of the wetland, will improve the wetland's ecosystem services.

In summary, the current land use system (*Reference*) and the *Exploitation* land use options (expansion of wetland agriculture) show increased water yield, total discharge and higher peak flows resulting in a low potential for the regulating ecosystem services like reduction of flood peaks, climate regulation (carbon storage), and the recharge of aquifers in the wetland. On the other hand, *Conservation*, *Slope conservation* and *Protection of headwater catchment* land use options show a reduction in the total water yield, total discharge and peak flows in the inland valley by improving infiltration of precipitation and water storage. Consequently, the period for which water is available in the wetland will also increase. Another positive effect is that infiltration zones of natural vegetation at the wetland/upland interface can act as a buffer for sediment deposition and a biodiversity adaptation area (Wood and Dixon, 2008).

5. Conclusion

This study evaluated the impact of on-going land use and land use management practices on the water resources of a tropical inland valley catchment. To achieve this goal, an HRU-based interface (ArcSWAT2012) and a grid-based interface (SWATgrid) of the Soil and Water Assessment Tool (SWAT) model were applied to simulate the hydrological processes. Overall, a good representation of daily discharge dynamics was achieved by the two models with a realistic water balance. This is an important finding as both models have advantages and disadvantages. The HRU concept of ArcSWAT is computationally efficient but has no lateral exchange between the simulation units. Therefore, the spatial arrangement of the most important attributes soil, land use, topography is of minor importance which is acceptable for larger catchments. SWATgrid requires significant larger computing time but considers the spatial pattern in a landscape. In studies where this is of importance like in the catchment - wetland interaction as discussed here, this provides the possibility to evaluate management options which ArcSWAT does not offer.

Land use and land cover change impact was studied using four different scenarios each computed for the simulation period 2015/2016. Because the models are physically based, this simulation period is sufficient to emphasize the impact of LULC changes on the processes and to draw reliable conclusions. Both model setups indicated similar trends albeit difference in magnitude in the total discharge (surface runoff, lateral and groundwater flows) following the application of land use scenarios. A decrease in total discharge and annual water yield following land use management options in the order *Conservation* < *Slope conservation* < *Protection of headwater catchment* < *Exploitation* was found. Moreover, an increase in the total discharge and annual water yield for exploitation land use option was observed. From the analysis of FDC, adoption of the conservation management land use options will reduce the peak flows in the inland valley. Contrary, as a result of agricultural expansion (exploitation and current land use), runoff generation and flooding risks may increase related to higher peak flows. Consequently, an increase in the sediment and nutrient flows downstream can also be expected. Therefore, we emphasize adoption of conservation land use management strategies (operational land scape approach) which recognise wetland - catchment interactions for sustainable water resources management in the inland valleys. This is particularly important in East Africa, which is experiencing exorbitant pressure on the fragile water resource ecosystems like inland valley wetlands (once called "wastelands"), due to the changing climate and population growth.

Therefore, future efforts should focus on understanding the combined impact of climate and land use change on the water quantity and quality (sediments and nutrient flows) of these agriculturally used inland valleys in the region.

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Conflict of interest

The authors declare that they have no conflict of interest.

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